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Yb3+ doped ribbon fiber for high average power lasers and amplifiers

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ABSTRACT

Diffraction-limited high power lasers in the region of 10s of kW to greater than 100 kW are needed for defense, manufacturing and future science applications. A balance of thermal lensing and Stimulated Brillouin Scattering (SBS) for narrowband amplifiers and Stimulated Raman Scattering (SRS) for broadband amplifiers is likely to limit the average power of circular core fiber amplifiers to 2 kW (narrowband) or 36 kW (broadband). A ribbon fiber, which has a rectangular core, operating in a high order mode can overcome these obstacles by increasing mode area without becoming thermal lens limited and without the on-axis intensity peak associated with circular high order modes. High order ribbon fiber modes can also be converted to a fundamental Gaussian mode with high efficiency for applications in which this is necessary. We present an Yb-doped, air clad, optical fiber having an elongated, ribbon-like core having an effective mode area of area of 600 μm² and an aspect ratio of 13:1. As an amplifier, the fiber produced 50% slope efficiency and a seed-limited power of 10.5 W, a gain of 24 dB. As an oscillator, the fiber produced multimode power above 40 W with 71% slope efficiency and single mode power above 5 W with 44% slope efficiency. The multimode M^2 beam quality factor of the fiber was 1.6 in the narrow dimension and 15 in the wide dimension.

1. INTRODUCTION

In recent years the average power of fiber lasers has increased dramatically [3]. Up to 10 kW fiber lasers are now commercially available [4–6], but diffraction-limited high power lasers in the region of 10s of kW to greater than 100 kW are needed for defense, manufacturing and future science applications. A balance of thermal lensing and Stimulated Brillouin Scattering (SBS) for narrowband amplifiers and Stimulated Raman Scattering (SRS) for broadband amplifiers is likely to limit the average power of circular core fiber amplifiers to 2 kW (narrowband) or 36 kW (broadband).

A ribbon fiber, which has a rectangular core, operating in a high order mode can overcome these obstacles by increasing mode area without becoming thermal lens limited and without the on-axis intensity peak associated with circular high order modes. High order ribbon fiber modes can also be converted to a fundamental Gaussian mode with high efficiency for applications in which this is necessary [1][2]. Figure 1 shows the Yb-doped silica, air clad ribbon fiber fabricated at the Lawrence Livermore National Lab fiber draw tower facility [7]. Details regarding the fabrication, properties and performance of the fiber will be presented in section 2. In section 3, we will discuss the results and challenges of high order mode excitation in ribbon fibers with potentially non-uniform refractive index profiles. In section 4, we will present amplification of a single high-order mode in an optical fiber having an elongated, ribbon-like core with an effective mode area of area of 600 μm² and an aspect ratio of 13:1. In section 5, we will present the first multi-watt Yb-doped silica, high order mode ribbon fiber oscillator based on the same fiber.

The methods of launching into high order modes have been presented in previous papers and will not be covered here[1][7].

2. FABRICATINON AND CHARACTERISTICS OF THE YB3+ DOPED RIBBON FIBER

The fiber was fabricated via the Photonic Crystal Fiber (PCF) stack and draw method. Figure 1 shows the cross-section of an air-clad, ytterbium doped ribbon fiber. The is formed by 13 Yb-doped silica rods with an approximate doping level of 0.05 molar% Yb_2O_3 and 1.0 molar% Al_2O_3; the refractive index of the core was raised by 2.53×10^{-3} relative to the index of silica, forming a numerical aperture of 0.086 (custom glass supplied by Heraeus Tenvo, Inc). In order to form the double cladding, the core was surrounded by pure silica rods, and a silica tube. This preform was then stuffed into a second outer tube. The gap between the inner tube and the outer tube was filled with capillaries which form the air-cladding. All parts but the outermost tube were made of Heraeus F300 glass (< 1ppm OH); the outermost tube was silica supplied by Momentive, Inc (GE 214 silica, water content unknown).

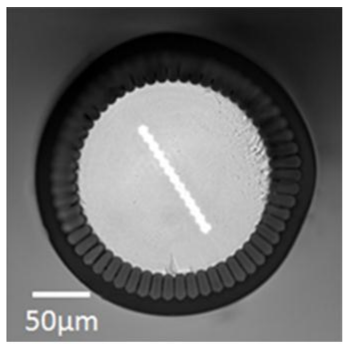

Figure 1, Yb-doped silica, air clad, ribbon fiber **[7]**.

The fiber's core was 8.3 × 107.8 µm. It supports a second order mode along its narrow dimension, but the second order modes in this dimension are very weakly guided. These modes are not seen in the seeded amplifier, or in the single mode oscillator. Both of these architectures are discussed in later sections. The pump cladding is formed by a ring of 57 holes, having inner and outer diameters of 167 µm and 245 µm respectively. The numerical aperture was measured to be NA = 0.3. The numerical aperture of the pump-cladding is modest, but it has been shown that the air-cladding technique can reach numerical apertures greater than 0.45[8], which would allow for higher pump powers.

3. MODE EXCITATION RESULTS IN PASSIVE AND YB-DOPED RIBBON FIBERS

In this section, the mode excitation results in a passive ribbon fiber will be discussed first. Next the amplifier experiment and results will be presented. The passive fiber, shown in Figure 2, had a pure silica core, and was index guided by a series of air holes. Using a mode launching technique based on binary phase plates, a high order mode (HOM) of the passive ribbon fiber was excited with 90% purity **[7]**. Purities of greater than 90% are theoretically possible.

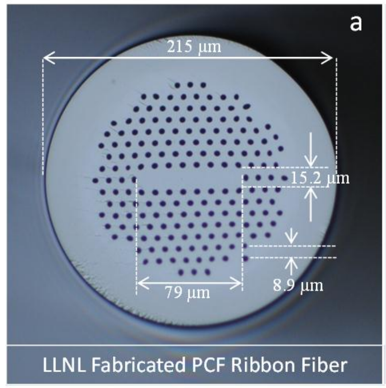

Figure 2, Pure silica, index guided, ribbon fiber **[7]**.

Figure 3 shows the cross-sectional lineout of both the theoretical (solid) and measured (dashed) modes. It is clear that there is strong agreement between the theory and the actual modes of this fiber, and that the binary phase plate mode excitation technique can successfully excite a HOM of a ribbon fiber.

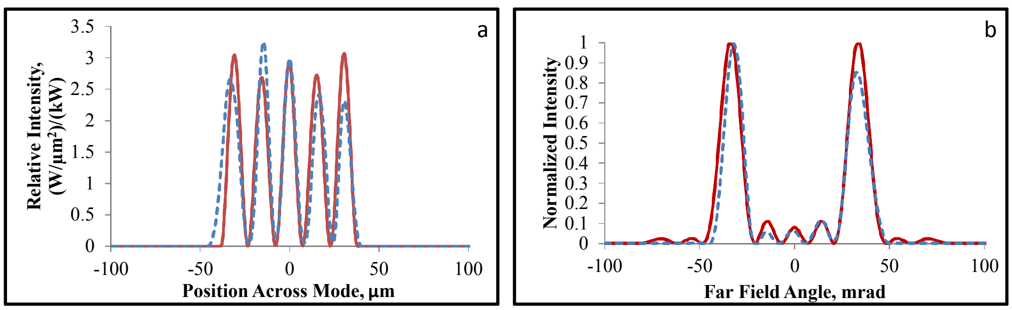

Figure 3, Theoretical (solid), and Measured (dashed) lineout of the m = 4 mode the pure silica, passive ribbon fiber of Figure 2. (a) near field (b) far field **[7]**.

The 2-D profiles of the calculated and measured HOMs of the passive ribbon fiber are shown in Figure 4 (a) and (b) respectively. This clearly shows a strong correlation between the expected mode of the fiber and the actual mode. A similar HOM of the Yb-doped ribbon fiber is shown in Figure 4 (c) which has an effective area of approximately 600 μm^2.

The far-field of the excited mode, Figure 4 (c), is qualitatively much like a standard ribbon fiber mode. The optical power is mostly confined to a pair of lobes at angles which are symmetric about the center. This suggests a pure mode. The near-field has an unusual and non-ideal envelope across the mode. Each of the lobes of the near field has variations in intensity. However, we believe this is an excited HOM of the fiber which differs from the ideal mode. This conclusion is reached because the mode profile is stable with amplification (presented below) and the same excitation method was successful with the passive ribbon fiber (presented above, and shown in Figure 4 (a-b)). We attribute the non-ideal mode shape to variations in the index of the Yb-doped core rods. This issue has also been discussed in connection with HOMs in circular core fibers[9]. A separate multiple-core ytterbium ribbon fiber effort demonstrated similar behavior of the individual power content in each particular near field lobe[10].

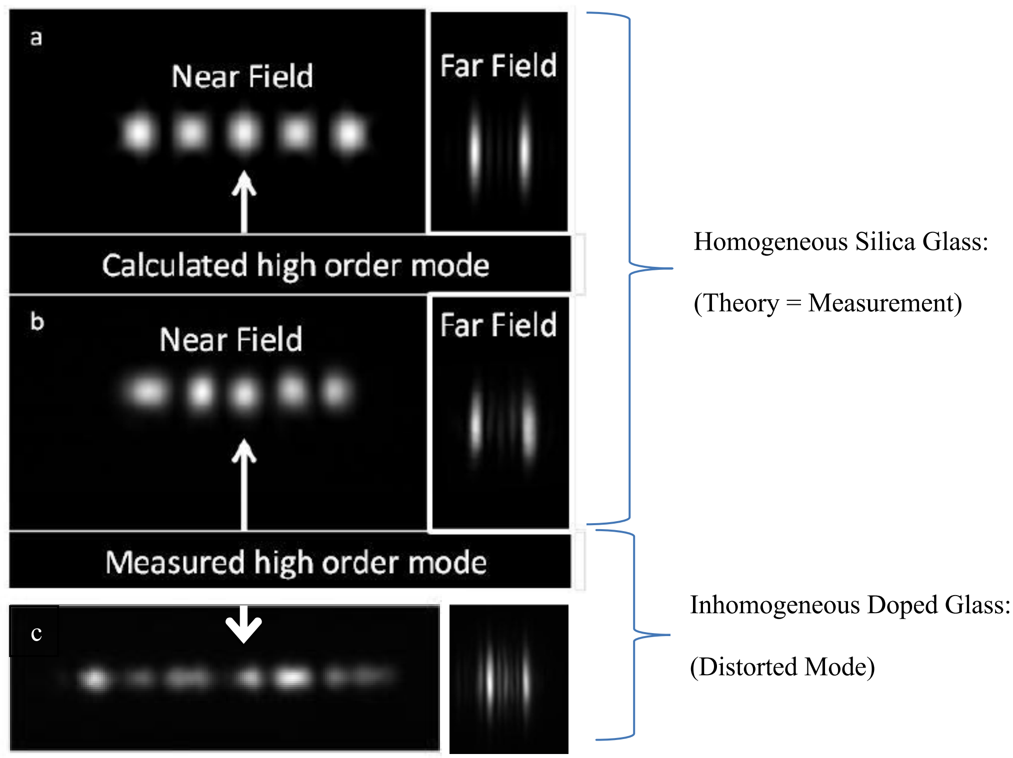

Figure 4, (a) calculated mode (m = 5) pure silica fiber. (b) measured mode (m = 5) pure silica fiber. (c) measured mode (m = 6) Yb-doped core fiber. The top two modes show good agreement between excited and calculated high order mode (HOM) for the pure silica fiber, while the lower mode shows an example of a HOM displaying a non-ideal envelope, possibly due to inhomogeneous refractive index of the Yb-doped rods forming the core **[7]**.

4. AMPLIFIER

The Yb3+ doped ribbon fiber described above was used in an amplifier configuration with a HOM excited by the binary phase plate method. Figure 5 shows the experimental setup of the amplifier. The mode launching scheme is presented as a black box but is described in greater detail in **[7]**. The optics were chosen to match the size and NA of the pump delivery fiber (105 µm, 0.15 NA) to the acceptance size and NA of the ribbon fiber cladding (167 µm, 0.3 NA).

The ribbon fiber amplifier was optimized to be ~ 6 m by cutting back another fiber sample until the maximum slope efficiency was achieved. The air cladding was collapsed at the very ends of the fiber so that a high quality angle cleave could be made on both ends to avoid oscillating off of the fiber end facets. The coupled pump power was determined by measuring the power coupled into a 10 cm piece of ribbon fiber and adjusting up to account for the approximate core absorption in the short sample. This pump coupling alignment was repeatable due to the pump mode size and NA being smaller than the amplifier cladding ID and NA.

Figure 6 (a) shows the signal output power v.s. coupled pump power and Figure 6 (b) shows the gain v.s. coupled pump power. The highest final output power of the amplifier was 10.5 W corresponding to a gain of ~ 24 dB with a slope efficiency of 50%. Improved slope efficiency could be accomplished by spatially matching the gain profile in the core to the mode of interest. Improved slope efficiency is reported in a later section for the multimode oscillator case.

The amplifier seed was only 38 mW. The amplifier can go to higher power, but we were only interested in the single mode regime. This amplifier became multimode above 20 dB of gain. We believe that the selected HOM of this amplifier became gain saturated and improved seed power would lead to higher single mode power. Alternatively, the modal purity degradation could also be due to thermal stresses on the uncooled pump side of the fiber.

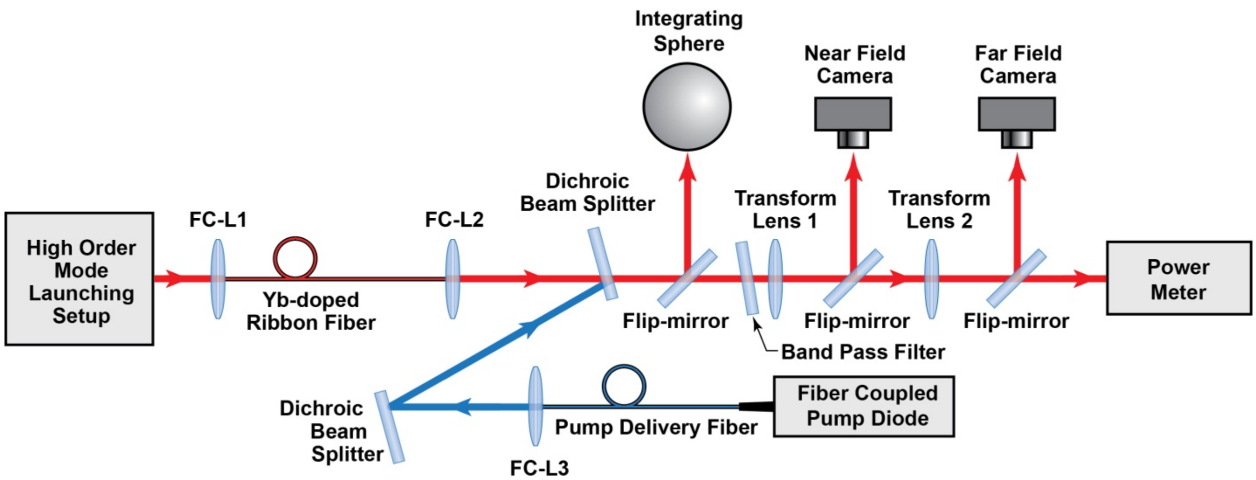

Figure 5, Yb-doped Ribbon fiber amplifier experimental setup **[7]**.

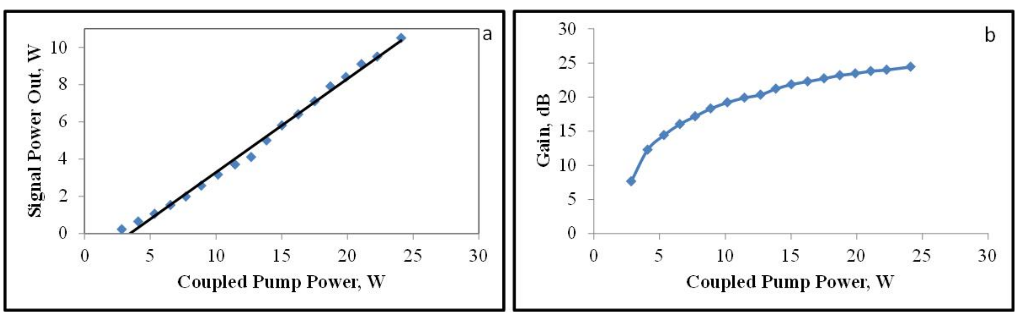

Figure 6, (a) Signal output power v.s. coupled pump power. (b) signal gain v.s. coupled pump power **[7]**.

The near and far field 2-D intensity profiles at various gain values are shown in Figure 7. The modal profile remains unchanged through most of the amplification curve indicating a single high order mode up to ~ 20dB of gain which corresponds to ~ 5 W of power. The near field profile of this mode is non-ideal compared to the modes observed in the pure silica case, but we believe it to be a pure mode of this fiber for the same reasons stated in section 3 for the amplifier case.

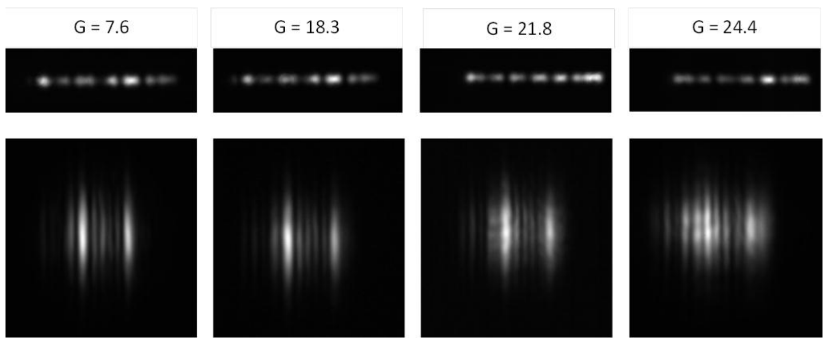

Figure 7, Yb-doped ribbon fiber amplifier HOM intensity patter at various gain values (near field – top, far field – bottom). Single HOM operation at G = 7.6, up to 21.8 dB. Some additional mode amplification observed at G = 21.8. Multimode operation apparent at G = 24.4. **[7]**.

This shows that a single high order mode of ribbon fiber amplifier can be excited and amplified, maintaining its mode until very high gain values.

5. OSCILLATOR

The same fiber was used to make a ribbon oscillator. Both the single mode and multimode cases were examined. Figure 8 shows the experimental setup for the ribbon fiber oscillator including the optional far field spatial filter. The filter consists of two slits which match the two primary lobes of a ribbon fiber HOM intensity pattern. The slits are adjustable to allow fine tuning of the mode selection.

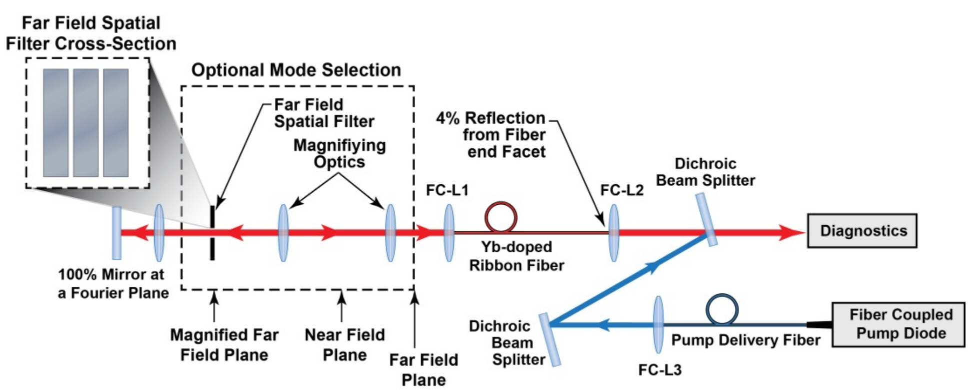

Figure 8, Experimental setup for single mode ribbon fiber oscillator with intra-cavity free space spatial filter [11].

The ribbon fiber oscillating off of the cleaved end facets of the fiber without any mode selection achieved multimode power above 40 W with 71% slope efficiency and, by including an external cavity spatial filter, achieved a single high order mode above 5 W with 44% slope efficiency. Figure 9 below shows the output power vs. coupled pump power in the multimode case, and Figure 10 shows the M^2 beam quality factor in both the narrow and wide dimensions respectively. It is clear from the narrow dimension beam quality measurement of $M^2 = 1.6$ that the core is not completely single mode in this dimension. However, even without any mode selection in this dimension, evidence of higher order mode content is not apparent in near field or far field beam profiles.

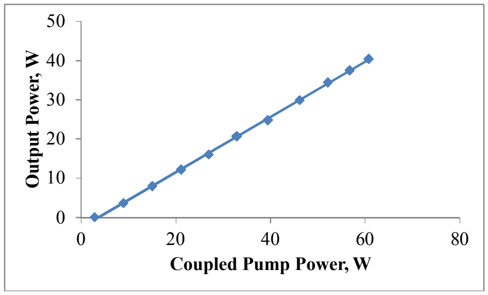

Figure 9, Output power v.s. coupled pump power for a multimode ribbon fiber oscillator showing 71% slope efficiency [11].

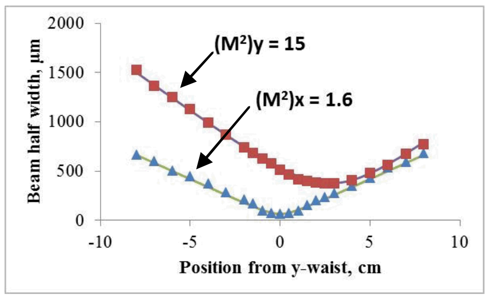

Figure 10, Beam waists profiles for both the x (narrow) and y (wide) planes. (M2)x = 1.6. (M2)y = 15 [11].

The superposition of the electric fields of each mode of a ribbon core fiber makes mode selection by spatial filter difficult in the near field. Far field spatial filtering is preferred due to the spatial separation of the primary lobes of each mode. A one dimensional amplitude mask with two transmission windows can be placed in the far field to transmit only the two primary lobes of the desired mode. Using this mask, intra-cavity selection of a single high order ribbon fiber mode can be achieved.

Figure 11 shows the output power vs. coupled pump power for the ribbon fiber oscillator using the 1-D intra cavity spatial filter. The mode was stable up to ~ 5 W with 44% slope efficiency. The near field (upper) and far field (lower) 2-D mode intensity profiles for various output powers are shown in Figure 12 demonstrating the stable mode. Like the amplifier case, this higher order mode of the fiber is also non-ideal in the near field, but the far field profile is closer to the expected mode profile and remains stable with increased power suggesting a real mode. The final image at 5.1 W shows the low level modal noise growing which shows a transition out of single high order mode operation into multimode operation. Like in the amplifier case, we attribute the non-ideal near field modal profile to possible inhomogeneity of the refractive index of the glass used to form the ribbon core.

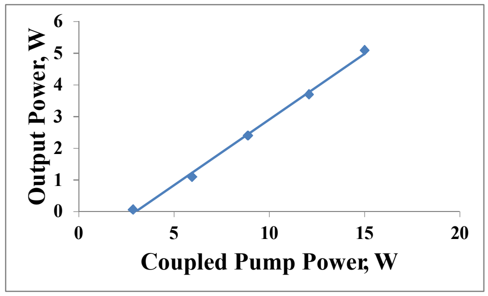

Figure 11, Ribbon fiber oscillator operating in a single high order mode. Output power v.s. coupled pump power showing a slope efficiency of 44 % [11].

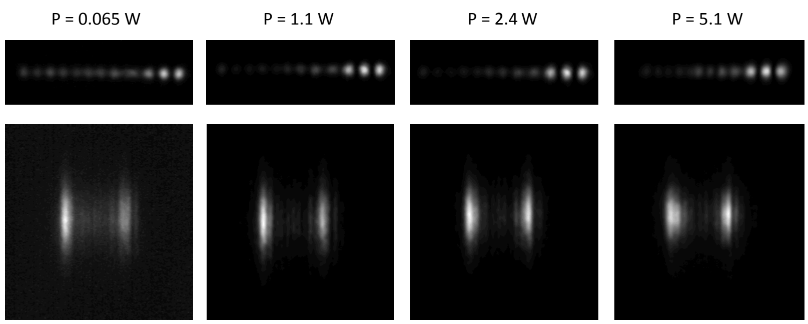

Figure 12 Near field (top) and far field (bottom) of a single high order mode ribbon fiber oscillator. The modal purity is nearly unchanged from threshold (0. 65 W) to 5 W [11].

Because the modes of the pure silica fiber match the modes which are expected for a uniform ribbon core, we were able to calculate the purity of the mode by using the Gerchberg-Saxton phase retrieval algorithm and a mode overlap integral **[7]**. We were not able to make the same overlap integral with the modes of the Yb-doped ribbon fiber because this method of calculating the modal purity requires prior knowledge of the modal content, and the modes of this fiber do not agree with the theory for a uniform core.

The ribbon fiber oscillator can operate in both the single high order mode (5 W) and multimode (40 W) regime. Additional improvements are expected with greater uniformity in the core glass refractive index as well as with the use of mode selective gain.

6. SUMMARY

Ribbon fiber oscillators and amplifiers show great promise in breaking through the nonlinear and thermal limits of traditional circular core fiber lasers. In this paper we have presented an Yb-doped ribbon core, double clad ribbon fiber with a 108 μm wide core with an aspect ratio of 13 to 1. This fiber was used to demonstrate amplification in a single high order mode and oscillation in both the single high order mode and multimode regime.

In the amplifier configuration, the double-clad, ytterbium doped, photonic crystal fiber produced 50% slope efficiency and a seed-limited power of 10.5 W, corresponding to a gain of 24 dB. The high order mode remained pure through 20 dB of gain without intervention or realignment.

In addition, we report the first multi-watt, Yb-doped silica, high order mode ribbon fiber oscillator, with multimode power above 40 W with 71% slope efficiency and power in a single high order mode above 5 W with 44% slope efficiency.

The modes of the fiber appear to be non-ideal. The active ribbon fiber might be improved by reducing rod-to-rod variations in the index of the Yb-doped core rods, to which we attribute the slightly distorted shapes of the fibers modes. A bigger improvement might result by doping the core to selectively amplify a target high-order-mode; that is, by alternating doped and un-doped core rods across the preform's core, a previously suggested approach [12,13].

Ribbon core fibers may ultimately provide the capability to produce laser amplifiers with 100 kW of diffraction-limited output power by mitigating the nonlinear effects that currently limit circular core fibers.

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